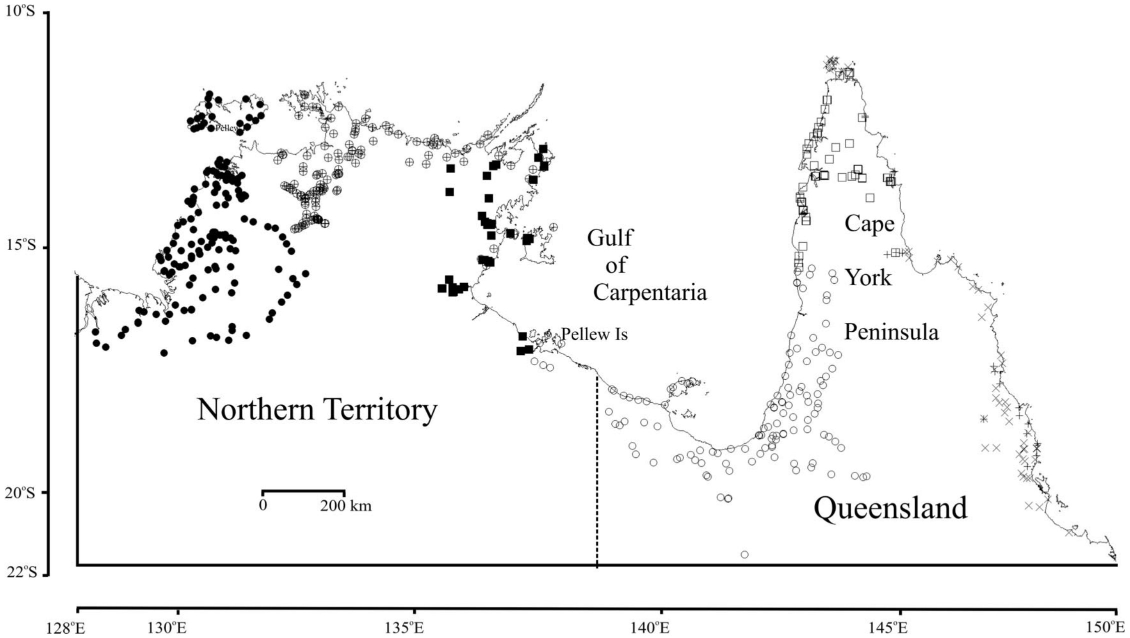

Fig. 1. *Anopheles* collection sites in northern Australia showing sampling localities by year. Sampling localities: +, 1985; □, 1986; ○, 1987; ■, 1988; ⊗, 1989; ●, 1990; and x, 1991.

using KnowledgeSeeker, to clarify the suite of environmental factors associated with the strictly coastal distribution of *An. farauti* s.s. in Australia.

Materials and Methods

Mosquito Surveys. Adult and larval *Anopheles* were collected along the coast of Queensland and the Northern Territory, and up to 300 km inland between latitudes 10 and 19° S and longitudes 128–146° E. Different sectors of this region were covered progressively yearly from 1985 to 1991 by using four-wheel-drive vehicles and Australian Army helicopters at the end of the wet season, as described previously (Cooper et al. 1995). Specimens were identified morphologically to species in the field, and transported to the laboratory in liquid N_2 for determination of isomorphic species by using either allozyme electrophoresis (Mahon 1984) or DNA-based probes (Cooper et al. 1991). All collection localities were recorded on 1:100,000 topographic maps at a ground resolution of 100 m^2 (Fig. 1).

Environmental Layers. Environmental information used in this study included ASCII raster grids covering northern Australia at a spatial resolution of 0.01° (≈1 by 1 km). The geographical extent was 10–22° S latitude and 128–150° E longitude, for 40 climatic and nonclimatic data layers (Table 1). These layers included 27 "bioclimatic" parameters of temperature, rainfall, and solar radiation generated with ANUCLIM (Houlder et al. 1999). This involved the use of monthly mean climate surface coefficients, generated by the thin plate smoothing spline technique ANUSPLIN (Hutchinson 2003) from Australian Bureau of Meteorology climate data, for the period January 1921 and December 1995 (Hutchinson and Kesteven 1998). Latitude and longitude of the meteorological stations were used as independent spline variables, together with a 0.01° digital elevation model (DEM) for northern Australia generated with ANUDEM (Hutchinson 1997), which acted as a third independent variable. Because atmospheric moisture is known to be a key factor influencing survival and longevity of adult mosquitoes, we included four layers describing dew point (January and July at 0900 and 1500 hours) generated with ESOCLIM (a component of ANUCLIM), and six layers for relative humidity (January, July, and annual mean at 0900 and 1500 hours), generated with ANUSPLIN (Hutchinson 2003) from long-term climate data from the Australian Bureau of Meteorology. We also included three nonclimatic layers: elevation (a DEM of 1 km ground resolution), slope, and aspect (both generated from the elevation DEM with the geographical information system [GIS] program TNTmips (MicroImages Inc., Lincoln, NE).

Boundary *U*-Test. This software tool permits exploratory analyses of species' range limits based on simple, univariate comparisons of conditions inside and outside of a user-specified range limit using Mann–Whitney *U*-tests to measure strength of association (Bauer and Peterson 2005). The application, recently presented as an ArcView GIS 3.3 extension (Bauer and Peterson 2005), first requires the user to specify a border that putatively corresponds to the range limit as well as points for analysis along that border. At each point, a rectangular transect of user-defined dimen-

tralia. The values of the four significant temperature variables, relating to diurnal, seasonal, and annual temperature ranges as well as lowest weekly minimum temperature, are higher in the arid inland areas of northern Australia and more moderate near the coast, so it is reasonable to postulate that they may be among the environmental factors that define the range of this species. Parameters associated with precipitation were not among the environmental factors ranked as significant by data mining or the boundary *U*-test. It is possible that the propensity of *An. farauti* s.s. to breed in brackish water might obviate the need for freshwater larval sites replenished by rainfall.

Recognition of atmospheric moisture as a critical variable associated with good-quality models accords with many field and laboratory observations on the biology of mosquitoes which have shown that adult survival is influenced by humidity (Clements 1963). Both data mining and boundary *U*-test methods indicated that long-term mean values for dew point and relative humidity in July were strongly associated with the range of this species. This time of year coincides with the middle of the northern Australian dry season, when aerial moisture is generally near annual minimum levels. The actual values of these indices in coastal areas are higher, owing to the moderating influence of the sea, than in neighboring inland areas. This association implies that the ecological niche of this species is influenced by higher atmospheric moisture near the sea as well as by steep elevation gradients immediately inland from the coast.

Acknowledgments

This work was funded by National Health and Medical Research Council of Australia Grant 211608.

References Cited

Anderson, R. P., D. Lew, and A. T. Peterson. 2003. Evaluating predictive models of species' distributions: criteria for selecting optimal models. Ecol. Model. 162: 211–232.

Bauer, J. T., and A. T. Peterson. 2005. Visualizing environmental correlates of species' geographical range limits. Div. Distrib. 11: 275–278.

Biggs, D., B. de Ville, and E. Suen. 1991. A method for choosing multiway partitions for classification and regression trees. J. Appl. Stat. 18: 49–61.

Breiman, L., J. Friedman, R. Olshen, and C. Stone. 1984. Classification and regression trees. Wadsworth, Pacific Grove, CA.

Cadenasso, M. L., S.T.A. Pickett, K. C. Weathers, and C. G. Jones. 2003. A framework for a theory of ecological boundaries. Bioscience 53: 750–758.

Clements, A. N. 1963. The physiology of mosquitoes. Pergamon, Oxford, United Kingdom.

Cooper, L., R. D. Cooper, and T. R. Burkot. 1991. The *Anopheles punctulatus* complex: DNA probes for identifying the Australian species using isotopic, chromogenic and chemiluminescence detection systems. Exp. Parasitol. 73: 27–35.

Cooper, R. D., S. P. Frances, and A. W. Sweeney. 1995. Distribution of members of the *Anopheles farauti* complex in the Northern Territory of Australia. J. Am. Mosq. Control Assoc. 11: 66–71.

Cooper, R. D., S. P. Frances, D.G.E. Waterson, R. G. Piper, and A. W. Sweeney. 1996. Distribution of Anopheline mosquitoes in northern Australia. J. Am. Mosq. Control Assoc. 21: 656–663.

Fagan, W. F., M. J. Fortin, and C. Soykan. 2003. Integrating edge detection and dynamic modeling of quantitative analyses of ecological boundaries. BioScience 53: 730–738.

Grinnell, J. 1917. The niche-relationships of the Californian thrasher. Auk 34: 427–433.

Houlder, D., M. Hutchinson, H. Nix, and J. McMahon. 1999. ANUCLIM version 5 user guide. Centre for Resource and Environmental Studies, Canberra, Australia.

Hutchinson, M. F. 2003. ANUSPLIN version 4.2 user guide. Centre for Resource and Environmental Studies, Australian National University, Canberra, Australia.

Hutchinson, M. F. 1997. ANUDEM version 4.6. Centre for Resource and Environmental Studies, Australian National University, Canberra, Australia.

Hutchinson, M. F., and J. L. Kesteven. 1998. Monthly mean climate surfaces for Australia. Centre for Resource and Environmental Studies, Australian National University, Canberra, Australia. (http://cres.anu.edu.au/outputs/climatesurfaces).

Levine, R. S., A. T. Peterson, and M. Q. Benedict. 2004a. Distribution of members of *Anopheles quadrimaculatus* Say s.l. (Diptera: Culicidae) and implications for their roles in malaria transmission in the United States. J. Med. Entomol. 41: 607–613.

Levine, R. S., A. T. Peterson, and M. Q. Benedict. 2004b. Geographic and ecologic distributions of the *Anopheles gambiae* complex predicted using a genetic algorithm. Am. J. Trop. Med. Hyg. 70: 105–109.

Mahon, R. J. 1984. The status and means of identifying the member of the *Anopheles farauti* Laveran complex of sibling species, pp. 152–156. *In* J. H. Bryan and P. M. Moodie [eds.], Malaria. Proceedings of a Conference to Honour Robert H. Black, February 1983, Commonwealth Institute of Health, Sydney, Australia. Australian Government Publishing Service, Canberra, Australia.

Peterson, A. T., and K. P. Cohoon. 1999. Sensitivity of distributional prediction algorithms to geographic data completeness. Ecol. Model. 117: 159–164.

Scachetti-Pereira, R. 2003. DesktopGarp. (http://www.lifemapper.org/desktopgarp).

Soberón, J., and A. T. Peterson. 2004. Biodiversity informatics: managing and applying primary biodiversity data. Philos. Trans. R. Soc. Lond. B 359: 689–698.

Stockwell, D., and D. Peters. 1999. The GARP modeling system: problems and solutions to automated spatial prediction. Int. J. Geogr. Inf. Sci. 13: 143–158.

Sweeney, A. W. 1987. Larval salinity tolerances of the sibling species of *Anopheles farauti.* J. Am. Mosq. Control Assoc. 3: 589–592.

Van den Hurk, A. F., D. J. Nisbett, P. N. Foley, S. A. Ritchie, J. S. Mackenzie, and N. W. Beebe. 2002. Isolation of arboviruses from mosquitoes (Diptera: Culicidae) collected from the gulf plains region of northwest Queensland, Australia. J. Med. Entomol. 39: 786–792.

Received 31 January 2006; accepted 20 June 2006.